Physical Models and Dynamic Simulation of Loose Soils as Component of the ICI Station

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I. VIRTUAL REALITY AND ROBOTICS IN NATURAL ENVIRONMENTS

In the fields of robotics, there has always been a constant need for the prediction of the robot's behavior in its environment, in order to test vehicle concepts, path planning procedures or control processes. Moreover, man wants or has to operate on inaccessible sites, which are too far away or inhospitable. Thus, intervention robots will be in charge of working on natural sites (planetary exploration, vulcanology, intervention in polluted areas, sea bed, ...). These have extremely variable geometrical characteristics in time (deformations, collapse, ...) and in these cases the robots have complex dynamic behavior (skidding, spinning, sinking).

The kinematics and geometrical modeling were effective for manufactured sites, where they allow to plan and control the path of motor vehicles in well-defined and geometrically stable areas, or in areas designed according to the robots characteristics. But they proved to be ineffective in natural sites. Indeed, these sites are in permanent evolution, and then, these methods predictability are not sufficient enough. The most judicious would be to exploit a model based on the environment physical criteria rather than the geometrical ones.

Furthermore, the tasks executed by the robots are sometimes too complex to be completely autonomous. Man and its analysis capacities are necessary and must be reintroduced in the decision loop of the prediction phase. Virtual Realities enable the collaboration of the operator and the robotic system for these complex cases. Thus, man is faced to an interface which makes it possible for him to drive the robot. This driving situation must be realistic, and the operator must feel the necessary information (image, gesture and sound) and act on the object that he perceives in front of him. This is a situation of direct driving and on-line decision similar to real driving. Obviously, this system permits to teleoperate a robot, but the virtual realities offer an additional advantage : they may be used at the three prediction levels required in robotics, which are conception path planning and control. In this way, before the actual execution of a given task, it can be virtually experienced and practiced in order to test whether it can be carried out.

This is why dynamic simulation and force feedback are two necessary aspects of this virtual reality system. Usually, the current virtual reality systems do not jointly include both aspects. They begin to appear under the form of a dynamic simulation with no external control and of a "simulated" force feedback. But force feedback means, for the driver, to perceive the vehicle's behavior in a proprio-tactilo-kinaesthetic manner, and is necessary in any driving situation where dynamic behaviors are prevailing. Physical modeling and simulation must be essential components of virtual reality simulation systems in the field of robotics.

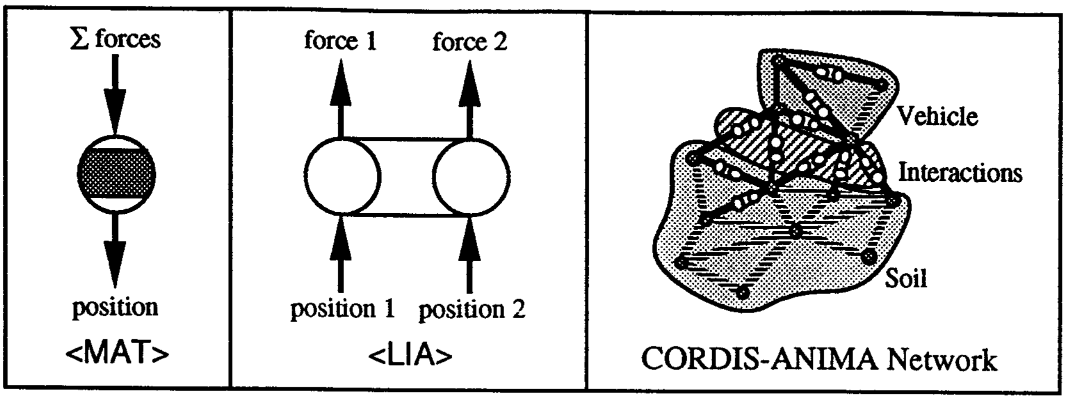
II. THE ICI STATION DESCRIPTION OF THE CORDIS-ANIMA MODELER AND OF THE "CRM", FORCE FEEDBACK CONTROL SYSTEM

The concept of Instrumental Communication Interface developed in the ACROE team led to the development of a Virtual Reality system prototype, presented here in the fields of robotics. The system is composed of :

1. a Modeler-Simulator of physical objects called CORDIS-ANIMA

The ACROE team has designed since 1984 a computer formalism, called the CORDIS-ANMA system [CLF84], [LC84], [CLF93], [Luc91], which combines a physically-based modeler and a physically-based real-time simulator.

The fundamental choices of this modeler-simulator is the particle physics paradigm, based on the physical interactions between punctual masses. In this formalism, a physical object or a set of objects are modeled and simulated in real time as a set of punctual masses linked by centered interaction chains. The most basic ones are linear elasticity and viscosity combined by finite state automata processes, allowing the description of any kind of non-linear interaction. Between masses, interactions can be put in parallel, and the conjunction of each functionality allows the creation of very complex interactions. By these means, we can create any kind of deformable materials (rigid, elastic, plastic, friable...), of complex materials (pastes, soils, wood, metal, sand, mud...) and of complex object assemblies (articulated objects, collisions, dry friction, adherence, sticking...) [Luc91]. With the choice of punctual physics, an object or a scene is calculated as a great number of few simple algorithms that may run in parallel performing real-time simulation. Any physical object or set of objects is represented by a network composed of two kinds of components : the mass component (in gray) and the interaction-without-mass component (in white) (fig. 1).



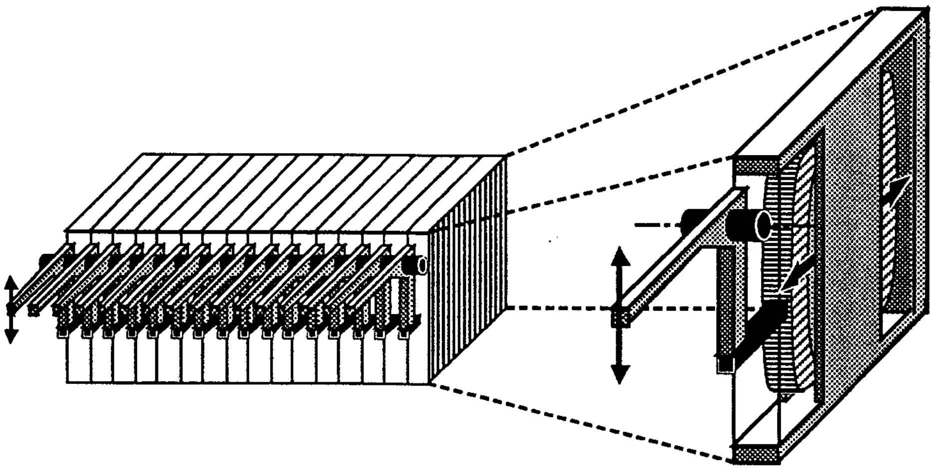
(fig. 1) The CORDIS ANIMA formalism used for the modeling of soils, vehicles and interactions between soils and vehicles.

2. a Force Feedback Gestural Transducer, called FFGT

ACROE has introduced in 1978 the force feedback principle in a computer sound synthesis context [Flo78]. Its first force feedback prototype was a 1D stick performing large-scale displacements (50 cm), high force feedback (60N peak) and high dynamic performance (at least 1 kHz). With this device and an analog computer, some experiments were realized, as for instance a highly rigid virtual wall or a highly realistic rack rail with hard notches and holes.

The second step of the ACROE was the obtaining of compacity [CLF84]. The second prototype had the same dynamic characteristics and a smaller size, about 15cm*15cm*20cm.

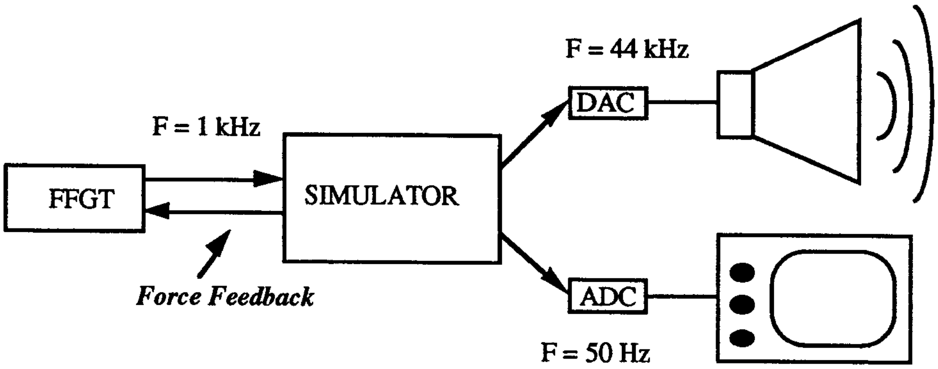
Our last prototype [CLF90] -called CRM as Force Feedback Modular Keyboard ("Clavier Rétroactif Modulaire" in French)- has about the same range of dynamic characteristics but in the same range of size, it has sixteen degrees of freedom. The breakthrough is simultaneously in compacity, versatility of the external morphology and in the high number of degrees of freedom. An international license covers its modularity principles as well as its engine technology, specially developed to achieve the today's desired performances.



(fig. 2) Force Feedback Modular Keyboard

3. a Real Time Simulator *called TELLURIS*

The TELLURIS simulator is the computing machine in charge of the real-time simulation of physical models. This is done by the computation of all the algorithms attached to each of the elementary components (mass and interaction-without-mass component) which compose the CORDIS-ANMA network representing the simulated physical object. The real time constraints are very high. Indeed, the computation has to be achieved in less than one millisecond. Thus, the inside processors have to be powerful (about one Gflop or more). The external interfaces are also high performing : the simulator is connected to the force feedback modular keyboard and the Inputs/Outputs between the simulator and the keyboard are performed simultaneously and synchronously at the frequency of 1 kHz. At the same time, the simulator is connected to loud speakers and to a screen, where the output transmissions are performed at 44 kHz for the former and 50 Hz for the latter.



(fig. 3) The Real Time Simulator Inputs/Outputs

Note : The works presented here and the patent of the CRM are supported by the French MINISTERY of CULTURE.

III. MODELS OF LOOSE SOILS

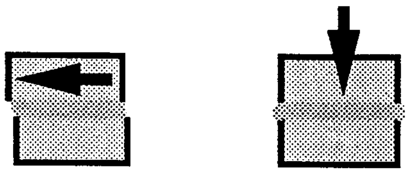
The work presented here corresponds to the study and the development of CORDIS-ANIMA models of vehicle-soil systems in the field of planetary robotics. These models satisfy the architectural constraints of the ICI station. Thus they are portable without any modification on this station and would be easily connected to its force feedback system.

1. Models of loose soils

In previous works [JLL91], the principles of CORDIS-ANIMA enabled the modeling of rigid soils with a complex profile and of soils constituted of a rigid substratum covered with moving stones. The models tackled here are loose soils of any profile, sandy or muddy, whose behavior are viscous-plastic deformation, shear and collapsing. These soils may be subjected to irreversible deformations under the weight of a vehicle. When they are modeled by an agglomerate of elements, their simulation is time consuming and such modeling is not necessary in the study of usual grounds. Thus, the principles of CORDIS-ANIMA enabled the modeling of optimized loose soils according to the criteria of a layer of variable thickness initialized arbitrarily, put on a non-granular rigid or deformable substratum of any profile.

2. Physical characteristics of loose soils

As any object, a soil can be subject to two types of constraints : longitudinal in compression (or traction) or transverse in shearing (fig. 4).



(fig. 4) Shear and packing constraints on a test tube

In compression, the soil packs down and the interstices between the soil particles (filled with air, water,...) are reduced and the particles move. While moving, the fluids or gas in the interstices, and specially the particles, resist. This resistance increases in an exponential way. When the particles cannot move anymore, the particles are in compression.

In shearing, the matter plans move along each other. The soil resistance to the constraint is the consequence of two phenomena : particles friction and cohesion. The first one is proportional to the load, perpendicular to the shear plan, the second one is constant. The value is varying, from very high for clay to “zero” for dry sand.

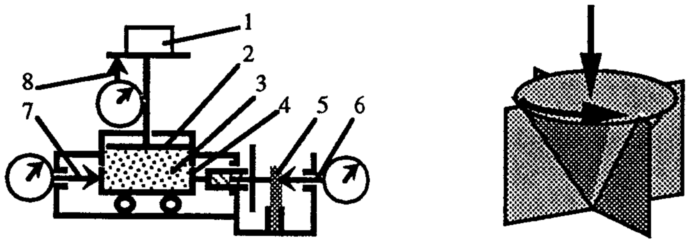
The Mohr-Coulomb equation takes into account both friction and cohesion :

$$\tau = c + \sigma.\tan Ø$$

with τ : shear resistance (kPa)
c : cohesion (kPa)
σ : normal pressure (kPa)
Ø : angle of internal friction

Moreover, as for any material, three phases in the behavior can be observed. First, for low constraints, in the elastic zone, the material returns to the initial state once the constraint is not applied anymore. Then, in the plastic zone for a higher constraint, the material will not return to the initial position after the removal of the constraint. At last the material can break into pieces, if the constraint reaches a pre-defined value.
The plastic zone is obviously the zone we are interested in, since the vehicle's tracks remain on the soil.

There are several measurement methods (fig. 5). In laboratories, the measurement are performed on test tubes of soils constrained by presses adapted to the dimensions of the sample. In that way, it is possible to measure the bindings and constraints, and to determine the compression and shear resistance.



(fig. 5) System of shear measurement (1 : Vertical load weight ; 2 : Load piston ; 3 : Soil samples ; 4 : Motor vehicle ; 5 : Elastic small plate ; 6 : Measurement of the horizontal constraint ; 7 : Measurement of the horizontal displacement ; 8 : Measurement of the vertical displacement), cone-valve penetrometer;

In situ, cone valve penetrometers are used. The device is immersed and turned into the soil. During the penetration, the bearing strength of the soil is determined, while during the turning of the penetrometer the shear strength of the soil is determined.

The results of the penetration measurement give the penetration deepness in terms of the pressure. The measurements of shear strength give the shear resistance in function of the charge pressure.

The soil is a very complex material and its characteristics depend on numerous factors. They can be modified by humidity rate, capillary pressure, structural movements, fluctuations in the grounds hydrostatic level, underground water movements, historic constraints, time, chemical actions or environmental conditions [LM93].
One of the main factors is the packing, which causes the increase of cohesion forces. For Moon or Mars where the soils are pulverulent, this aspect is vital : nothing (rain, trampling) packed down the successive dust layers [Leo72].

3. The granular approach

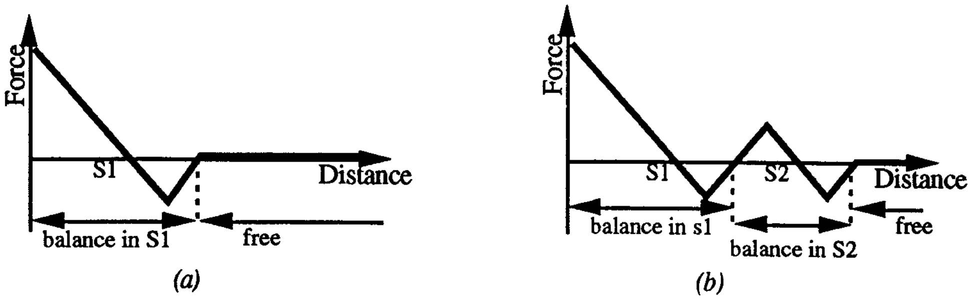
• Elementary interactions - Agglomerates

Talking about the granular approach of sand, the usual modeling of grains of sands is done via punctual masses in collision interaction. These masses form an agglomerate, and the plasticity of the soil is due to the rearrangements of grains in the soil. While moving, they change their position of stability and thus modify the shape of the soil.

In [HLM94], granular piles were modeled with a physically-based multi-scale model : an intermediate-scale model composed of punctual masses in threshold viscous-elastic interaction models the non-linear behavior of granular piles (piling, avalanches, collapses and arching) ; a physically-based small-scale model describes linear phenomena such as flow. Punctual masses linked together by a threshold viscous-elastic interaction define grains which are deformable spheres. In the following, this simple approximation of sand grains will be called grains.

Because of their high cost, these models were optimized.
1. on the one hand, by taking into account the specificity of the topological structure. In this way, loose soils are composed of more or less loose layers and are set on a rigid substratum.
2. on the other hand, in defining less elementary interaction functions than viscous-elastic collision interactions and more integrated interactions, the trial is to directly represent the horizontal and vertical layers' plasticity.

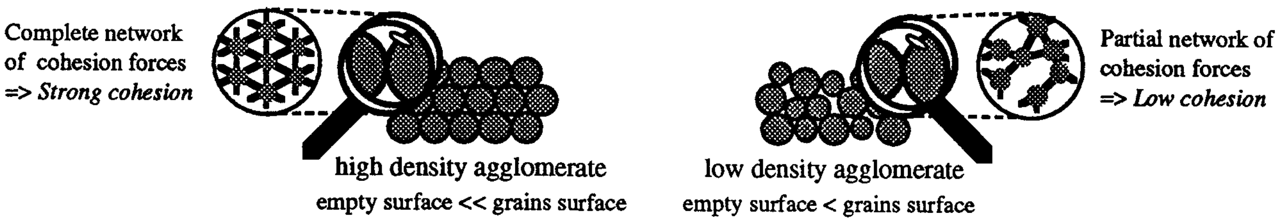
The plasticity of the modeled soil does not depend only on the number of elements and their position, but also on the interaction function used. Thus, the cohesion of the soil has to be included in the link element, since friction is caused by the collision interactions as the masses move along each other. Consequently, the various types of interactions used are based on a cohesive collision interaction (fig. 6.a).



(fig. 6) Cohesive collision interaction function with one or two states of stability

Several models have been developed according to this principle. The first two are composed of identical grains for the first and of grains of two different sizes for the second.

The density of the agglomerates obtained with the two methods are different (fig. 7). In the first case, the grains arrange regularly like atoms in a crystal, and the cohesion is strong. In the second case, the diameter irregularity creates larger interstices, and the cohesion is low which makes the reorganization of the grains easier.



(fig. 7) Agglomerate density and cohesion

The third model is based on a cohesion interaction, with two stability distances (fig. 6.b). These two stable states enable to model grains with two different visible bulks. It is possible to adjust the stiffness of the first stability to obtain a more or less fragile agglomerate. Furthermore, once compressed, the grains offer a higher cohesion and thus a higher resistance. This behavior is rather realistic for pulverulent soils.

To test the penetrability of agglomerates, a ball of various weight was put on the agglomerates. The different phases of a material behavior under a load have been observed :

• For a low weight, the agglomerate behavior is in the elastic zone. It is just compressed under the ball. If the ball is removed the agglomerate comes to the initial state ;

• For a high weight, the pressure overcomes the agglomerate breaking limit. The ball sinks totally ;

• Between both states, the ball penetrates the agglomerate, without sinking : this state is called the plastic state. Once the load is removed, the agglomerate does not go back to the initial state.

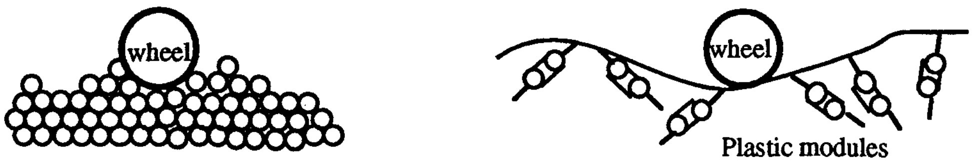
At last, for the plasticity test, the load of the ball is removed. This enables to observe the agglomerate evolution with no constraint and to determine its plasticity, i.e. its capacity to go back to the initial state.

These studies gave a classification of the models according to the type of the modeled soil. For a pulverulent soil, highly fragile and crumbly, the third model would be the best, whereas the second model is adapted to a sandy soil.

General results are as follows :

• First model : low penetrability, average plasticity (quite rigid soil)
• Second model : high penetrability, low plasticity (sandy soil)
• Third model : average penetrability, high plasticity (highly fragile pulverulent soil)

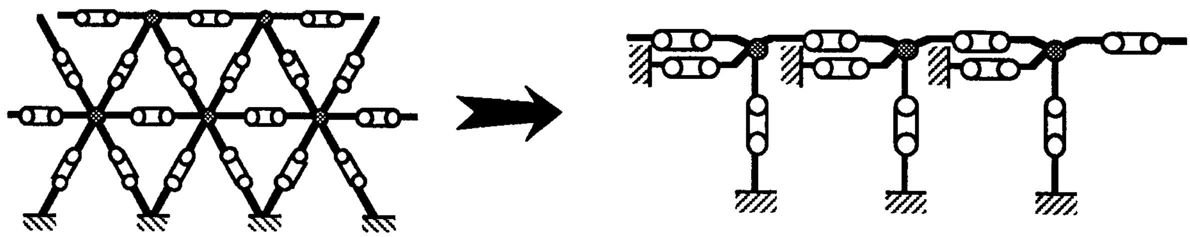
The advantages of this approach are simplicity and the possibility to simulate sinking. The vehicle is likely to modify the layout of the soil's masses, and can deeply sink. The drawback is the relatively high computation cost. However, if the soil does not reach the breaking threshold, it is not necessary to rearrange the soil's masses, and the plasticity is due to the link elements.



(fig. 8) Granular modeling of a loose soil : with particles and a plastic carpet

• Composite interactions - Plastic carpet

The structure of the soil is directly derived from the previous first model. It is triangular and regular. Only the interactions between neighboring masses were kept. All the others were useless and therefore were eliminated. This first type of structure was not satisfactory to model natural grounds, thus it has been simplified in order for the choice of parameters to be easier (fig. 9).



(fig. 9) Stratified and stitched soil - Plastic carpet

The new model developed does not use the triangular structure which is difficult since it does not dissociate the transverse efforts (shear) from the longitudinal ones (compression). Moreover, the soil stratification is not relevant. Indeed, the complex behavior of the subsoil can be introduced in the link elements, and that leads to remove the soil's lower layers.

From the characteristics of cohesion and soil resistance, a shear and compression resistance has to exist with the subsoil and the contact surface has to resist to dislocation.

Thus, the necessary interactions are as follows :
• Cohesion of the surface layer ⇒ plasticity with the neighboring masses ;
• Shear resistance with the subsoil ⇒ horizontal plasticity with a fixed point ;
• Compression resistance with the subsoil ⇒ vertical plasticity with a fixed point.

This model gives very good results. It enables to create any kind of natural profiles of grounds. It is also possible to set the subsoil more or less deeply to model a very thick loose soil, or on the contrary, a ground where the subsoil rocks come to the surface. The choice of parameters is easy, as it is easy to modify the interactions to improve the characteristics. Indeed, it is possible to determine the horizontal plasticity according to the vertical ones to improve the shear resistance in function of the compression.

IV. SIMULATIONS

1. The vehicles and their motorization

The CORDIS-ANIMA principles also allow the modeling and simulation of articulate rigid structures, including deformable objects, specially necessary to the representation of robots and vehicles. Thus, chassis of several vehicles were modeled, as well as the engines required for their propulsion.

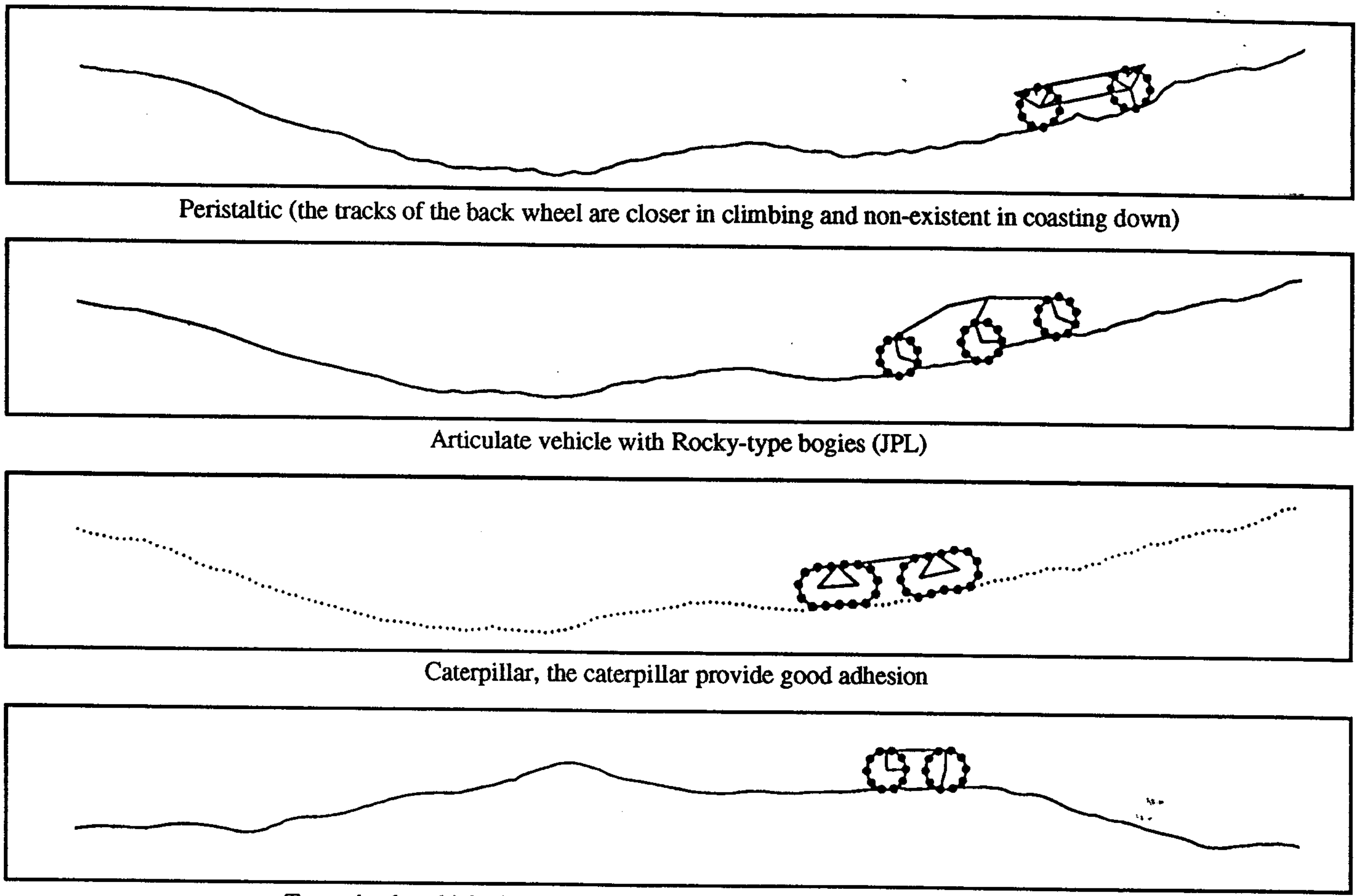
The vehicles chassis are composed of masses linked together with high stiffness elastic interactions. This construction mode is easy, similar to the construction of a tubular chassis, where the links would be the pipes and the masses would be the soldering connecting these pipes. The stiffness constraints are the same : it is necessary to triangulate and to add shrouds. The joints can be constructed with two masses defining a rotation axis. The wheels and bogies axes are defined in that way.

The vehicles' motorization is based on the basic CORDIS-ANIMA driver element [DLC93] : the *muscle*. It can directly be used to motorize the limbs of legged vehicles. The muscle can also alternately lengthen or contract a chassis, so that the vehicle is moving peristaltically, as a surveyor caterpillar. A rotating engine for wheels and caterpillars has also been designed. For this engine, the muscles run very much like the pistons of a star engine (as on aircraft propellers).

To obtain these various behaviors, it is sufficient to create the appropriate control module, where the latter may be dynamic. For instance, the control module of the rotating engine controls the speed in acting on the force generated by the pistons. The peristaltic control module will not activate the movement if the vehicle needs it to get over an obstacle.

2. The results

The performed simulations gave realistic phenomena : wheel tracks on the soil, packing of the soil under a spinning wheel. These results made it possible to study the abilities of a vehicle's in climbing obstacle. Moreover, the easy modeling of the vehicle allows fast modifications : this enables to see the influence of various factors on the obstacle-climbing ability : mass distribution, length and proportion, ground clearance, control, ...



Peristaltic (the tracks of the back wheel are closer in climbing and non-existent in coasting down)

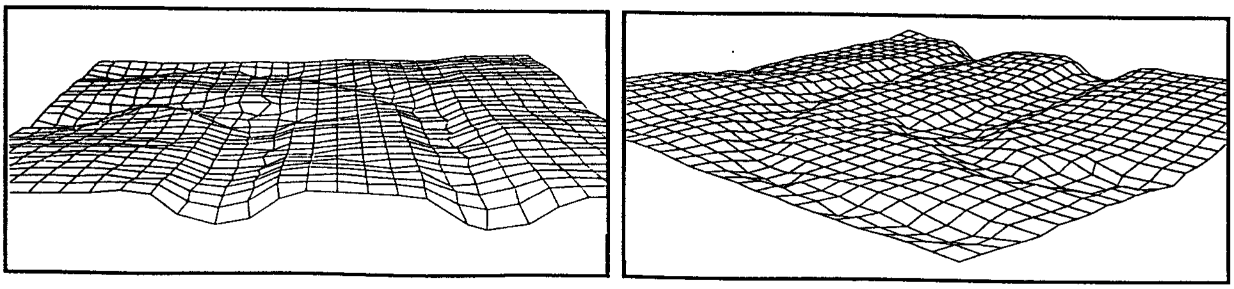
Articulate vehicle with Rocky-type bogies (JPL)

Caterpillar, the caterpillar provide good adhesion

Two wheels vehicle, its short chassis prevents it from climbing strong slopes

(fig. 10) Examples of vehicles and profiles of simulated soils

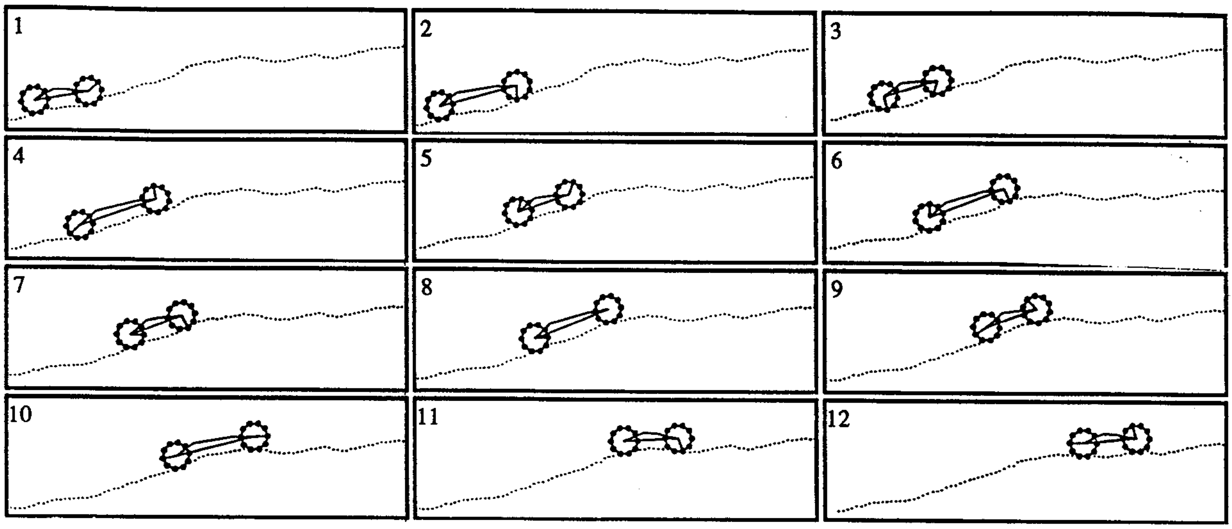
As it can be seen on the previous figure, the tracks left on a same soil profile may vary according to the type of vehicle (fig. 10). They also vary with the engine control parameters, which influence the vehicle's behavior and thus the soil.



(fig. 11) Example of tracks left by a four-wheels vehicle on a 3D soil

V. CONCLUSIONS

The models realized thanks to the plastic carpet made it possible to simulate vehicles on various profiles of soils, in several situations of obstacle-climbing. The number of samples constituting the soil is high, 200 to 300 masses for 2D soils (fig. 10) and approximately 800 masses for 3D soils (fig. 11), so the deformation of the soil is very realistic.



(fig. 12) Progression of a climbing vehicle propelled by a peristaltic movement (one second interval)

One of the following steps of our works will be the modeling of high dimension 3D soils, where the vehicles may operate obstacles bypassing and may have complex paths, while improving the finesse of the soil-vehicle interactions behavior.

The simulator ability to generate commands through the CRM can be used off-line or on-line. Indeed, it makes it possible to define controls with the virtual robot from the very start, and to re-use them for the real robot in standard situations. Thus, the CRM enables to tele-operate the robot in difficult situations.

Moreover, the conception of a physical modeler-simulator permits to redefine the model from the behavioral data of the real vehicle. Indeed, if a vehicles moves on a soil where the plastic behavior, the friction coefficient or any other physical parameter do not fit the one expected, the real behavior and the prediction will differ. Nevertheless, if the physical parameters of the soil model are modified, the simulator may calculate a new prediction again, so that the model fits reality. This kind of procedure is a new method to measure indirectly the physical parameters of a real soil.

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